Sensitivity of airborne-derived crop stress indices to the agricultural practices

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Abstract

When acquired both in optical and thermal infrared domain, remotely sensed data can provide a wide range of information about the status of a crop. Several studies have demonstrated the utility of such information for the development of stress indices that can be related to water, nitrogen or global physiological status of the plant.

In this paper, we investigate the relationships between crop biophysical parameters (LAI, SPAD, Humidity) and two airborne-derived spectral indices (NDVI: Normalized Vegetation Index, and CSI: Crop Stress Index) under different agricultural practices in terms of water treatment, nitrogen input and cultivar for sugarcane crop. We then discuss of the potentialities of the combined use of these two indices for a better understanding of crop status.

Introduction

Variable-rate technologies and site-specific crop nutrient or water management require real-time spatial information about the potential for response to in-season crop management interventions. Thermal and spectral properties of canopies can provide relevant information for non-destructive measurement of crop stresses. Thanks to the development of numeric cameras and the miniaturisation of the thermal sensors, remote sensing methods are now easier to implement for operational monitoring.

Nitrogen or water status of the plants has an effect on the spectral and thermal response of the canopy. Nitrogen status affects the leaves' chlorophyll content (Penuelas and Filella, 1998) altering the canopy reflectance in the red band (chlorophyll absorption band). Water status affects the leaf transpiration resulting in changes in the leaf temperature - this mechanism is also valid when the canopy is considered as a whole (Idso and Baker, 1967). In consequence, plant temperature has long been recognized as having potential to determine the water status of crops (Idso, 1982; Jackson et al., 1981). Any stress occurring over long periods of time will also affect the crop development (vegetation cover, LAI) and can be observed in the red, near-infrared (Ripple and Schrumpf, 1987; Penuelas et al., 1993) and thermal bands.

For crop monitoring, spectral measurements are generally made to develop indicators. Well known, the Normalized Difference Vegetation Index - NDVI (Rouse et al. 1973), based on near infrared and red reflectance measurement, is an indicator of the photosynthetic activity of the vegetation. More Recently, (Rodriguez et al. 2005) proposed a Canopy Stress Index - CSI, based on the difference between the canopy temperature (Tc) and the air temperature (Ta), normalised by vapour pressure deficit (VPD).

Few studies have focus on the effect of cultural practices on canopy temperature-derived stress indices. When applied at field scale, new questions emerged such as the sensitivity of such a index to cropping practices (cultivar and nitrogen input).

To respond to this question, in 2007, an experiment was conducted in Reunion (an overseas French department in the Indian Ocean) over sugarcane trials conducted with different practices (variety, irrigation, nitrogen). Visible, Near Infrared and Thermal Infrared measurement were acquired using an ultra-light aircraft, and used to derive crop stress indices. These indices were related to ground measurement in order to quantify their stability through time, and to test their sensitivity to various cropping practices.

Materials and methods

The investigation took place in Reunion Island, over a 5 ha sugarcane experimental field. From May to September 2007, seven airborne campaigns coupled with ground measurements were conducted.

Study site description

The sugarcane experimental field is located in La Mare, Sainte Marie, in the northern part of Reunion Island. Two cultivars (R579 and R570) were combined with three nitrogen inputs (noted 0/N, 65/N, 130/N in kg ha^{-1}) under two water treatments (irrigated or rainfed) making twelve treatments in a randomized block design with three replicates. For each combination of treatments (variety, nitrogen, irrigation), the size of the plot in the blocks was 135 m^2 and was made up of five rows each of 18 m length with a 1.5 m inter-row distance (Fig.1)

The sugarcane field was in the 5^{th} ratoon and in the 7^{th} month of growth when the experiment began. In the study area the mean annual rainfall amount is 1514 mm. On the irrigated blocks, the irrigation stopped on 5 September.

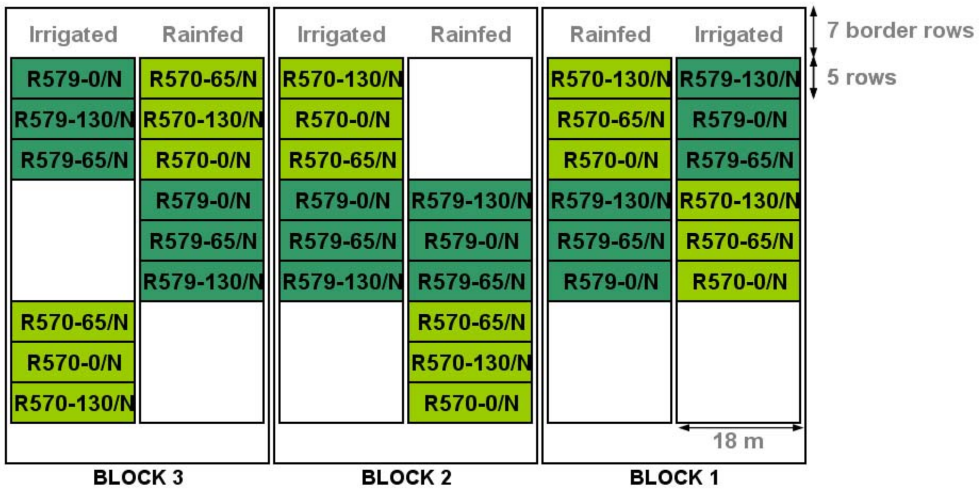

Fig.1 – Layout of the experimental field

Crop, radiometric and weather in-situ measurements

Crop measurements were done on the 36 trial plots, monthly, but not simultaneously with the airborne acquisitions. In order to not damage the crop, remotely studied, we carried out less possible destructive measurements.

The nitrogen status was estimated by measuring the chlorophyll content of the leaves with an optical chlorophyll-meter (SPAD-502, Konica Minolta). A relative green leaf area index (LAI) was calculated thanks to an algometric relationship linking the area of the leaves to the stalk heights and the number of green leaves. At last, humidity was approached using sheaths water content measurements.

In order to correct the atmospheric effects on thermal infrared airborne acquisitions, ground surface temperature data were acquired simultaneously with airborne acquisitions on cold (sugarcane canopy), hot (dark cloth) and intermediate (grassy road) targets using a hand-held infrared thermometer (KT19, Heitronics). Due to the height of the sugarcane, this thermometer was mounted on a mast for vertical acquisitions over the canopy to avoid angular variation between airborne and *in situ* measurements.

During the airborne acquisitions, the air temperature and relative humidity were recorded at 5 min intervals in a data logger. The daily rainfall and global radiation were obtained from a weather station located near the experimental site (Fig.2)

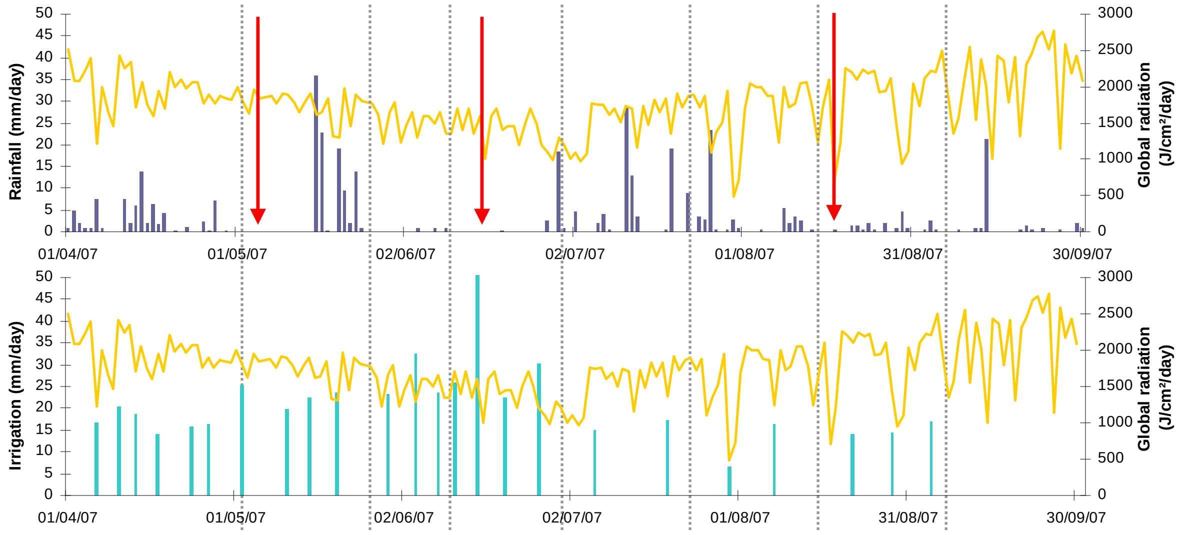

Fig.2 – Daily sum of global radiation and rainfall/irrigations during the experiment (La Mare, CIRAD). Grey dotted lines show the airborne acquisition dates. Red arrows locate dry periods.

On 24th September, date of field harvest, the final yield was collected for each plot.

Airborne acquisition system

The data acquisition system consisted of an ultra light aircraft equipped with sensors that measured the sunlight reflected in four different spectral bands and the radiation emitted by the Earth surface.

To measure the radiometric signal in the visible RGB spectral bands (Red, Green and Blue), a commercial camera (EOS 400D, CANON) was used. Same type of camera was adapted and equipped with a 710 - 855 nm band pass filter (LDP LLC XNiteBPG) to measure the radiation in the Near Infrared (NIR) spectral band. The settings of the two cameras (aperture, shutter speed, and sensitivity) were unchanged throughout the experiment.

The radiation emitted by the canopy was also measured using a micro-bolometer thermal infrared (TIR) camera (B20 HSV, FLIR). The radiance, detected over the 7.5 - 13 µm spectral band, is expressed in temperature, assuming a target emissivity of 1. The system provides 240 x 320 pixels images with a radiometric resolution of 0.1°C and an absolute precision of 2°C.

Seven airborne data sets were acquired between May and September with identical cameras tuning. The images were acquired in vertical mode over the experimental field, at different altitudes recorded by a GPS (from 300 m to 1200 m) between 11:00 and 12:00 a.m solar time. At 600 m, the ground resolution of the images was 10 cm for those taken in the visible and near infrared bands and 65 cm for those acquired in the thermal band.

Data processing

Remotely sensed data

Several processing steps are necessary to retrieve comparable values of pixel under space and time. The corrections concern the geometry and the radiometry of the images and are due both to the sensor itself and to the acquisition conditions.

The geometric distorsions of the CANON cameras were very low (Pierrot-Desseilligny 2008) and consequently no geometric correction was applied.

Radiometric corrections of RGB and NIR Images

The signal measured by a numeric camera is not linear to the radiance of the target. Furthermore, the incoming radiation varies from one date to the other. In order to compare the digital counts measured all along the season, camera embedded radiometric interpolation, vignetting distortion, and incident radiation variations were corrected using methodologies presented by (Labbe et al. 2007).

Radiometric corrections of TIR Images

The thermal signal measured by the camera is a mix of the target signal and the atmosphere signal. In order to remove the atmospheric noise, we used transfer functions established between the soil and the aircraft temperature measurements, for each acquisition date and each altitude (Lebourgeois et al. 2008).

Calculation of indices

Indices were calculated from images acquired at 600 m altitude.

According to (Rodriguez et al. 2005), and based on the work of (Idso et al. 1981) and (Idso 1982), the canopy stress index is defined as the difference between canopy (Tc) and air temperature (Ta), normalized by vapour pressure deficit (VPD):

$$CSI = (Tc - Ta) / VPD \ (°C/kPa)$$

As well as water inputs, a lot of factors can cause stomacal closure and thus have consequences on the canopy temperature, like for example nutrient shortages (Broadley et al. 2001; Radin et al. 1985). Consequently, the CSI is an index of the general physiological status of the crop, expected to be positive and high when plant is under stress.

From Red and NIR acquisitions, we derived the normalised difference vegetation index (Rouse et al. 1973):

$$NDVI = PIR - R / PIR + R$$

where R and PIR are the reflectances recorded by the sensors in the red and near infrared spectral bands respectively. In our case, the index is calculated using the digital numbers recorded by the cameras in these two spectral bands, normalized as described previously.
Both influenced by leaf chlorophyll content and canopy development, the NDVI is an indicator of the photosynthetic activity of the vegetation.
The mean NDVI and CSI for each plot were then calculated after subtracting one metre buffer from the original edge of the plot polygon to eliminate mixed border pixels.

Results and discussions

Crop parameters (Fig.3)

For irrigated crop, the quasi stability of the LAI values indicates that crop growth is almost finished. For high nitrogen inputs (65/N – 130/N), the crop was even fully covered from the beginning of the experiment (LAI above 4.5). For rainfed plots, the vegetation continues its growth up to end of august. The effects of the nitrogen treatment, water treatment, and cultivar are strong. The LAI difference is about 1 point between the lowest and highest nitrogen treatments during the whole experiment. The same difference is observed for water treatments at the beginning of the experiment. Values of LAI for R579 cultivar are always higher than those of R570 for irrigated treatment. The opposite effect is observed for rainfed treatment, showing a higher sensitivity of R579 to water treatment, while R570 is more tolerant.
SPAD observations are logically strongly influenced by nitrogen inputs with high values for the highest nitrogen treatments. Differences can also be observed between irrigated and rainfed treatments with a higher temporal variation and lower SPAD values for rainfed plots. SPAD records of rainfed plots are also marked by two dry periods (Fig.2). No cultivar effect is noticed. However, all figures show a decrease in SPAD values with time whatever the treatment (effect of plant senescing).
Sheath humidity varies with water inputs but also decrease with time due to plant physiology changes. For rainfed treatments, the decrease is punctuated with dry events.
These results are in agreement with most of the studies and easily explained by the plant physiology.

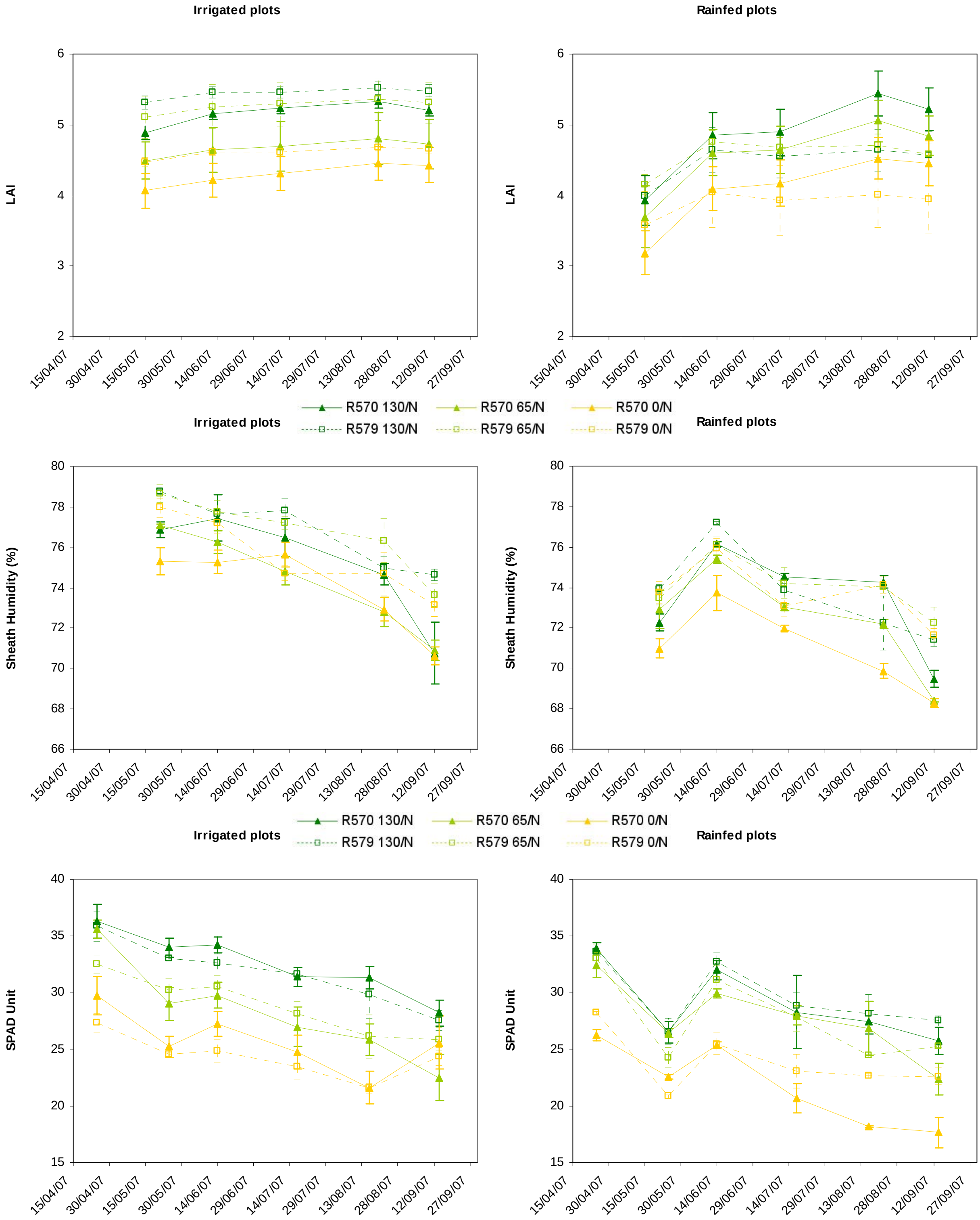

Fig.3 – Evolution of biophysical parameters (LAI, sheath humidity, SPAD) for each combination of “cultivar / nitrogen input” under irrigated (left) and rainfed (right) mode. Error bars indicate ± 1/2 standard deviation of the mean (n = 3).

Radiometric measurements (Fig.4)

In this part, the links between airborne-derived indices and crop parameters are discussed.

Figure 4 presents the evolution of NDVI and CSI through time during the experiment.

For NDVI, a high variability between the different treatments is observed. The effect of water is important, resulting in a decrease of 0.15 NDVI between irrigated and rainfed crops for all dates. The significant difference in NDVI values for the three nitrogen treatments shows a high relation between the crop nutrition and the radiometric index. This effect is strongly marked for 0/N treatment for which values of NDVI are very low.

A cultivar influence can be noticed, but it appears less significant than those of nitrogen or water.

For all the combinations of treatments and cultivar, the temporal evolution of the NDVI shows an increase at the beginning of the experiment, followed by a general decrease (senescence) until the harvest. For rainfed plots, the end of increase period occurs later than for irrigated plots, and the decrease tends to be marked by accidents due to dry (decrease of NDVI) or rainy (increase of NDVI) periods (see Fig.2).

Concerning CSI, the effect of cultivar is not apparent. The main parameter that affects the index is the water status. CSI is always higher for rainfed plots, varying according to an alternation of rainy and dry periods (Fig.2).

For irrigated plots, CSI is stable through time, except an accident for the August acquisition. This increase of CSI is due to a reduction of the irrigation frequency coupled with a dry period. In July, the same irrigation frequency is observed, but it has been compensated by rainfalls (Fig.2) resulting in a stabilization of the CSI.

The effect of nitrogen treatments is not really marked, but for each acquisition date, CSI for 0/N treatments is always a little higher than other nitrogen treatments.

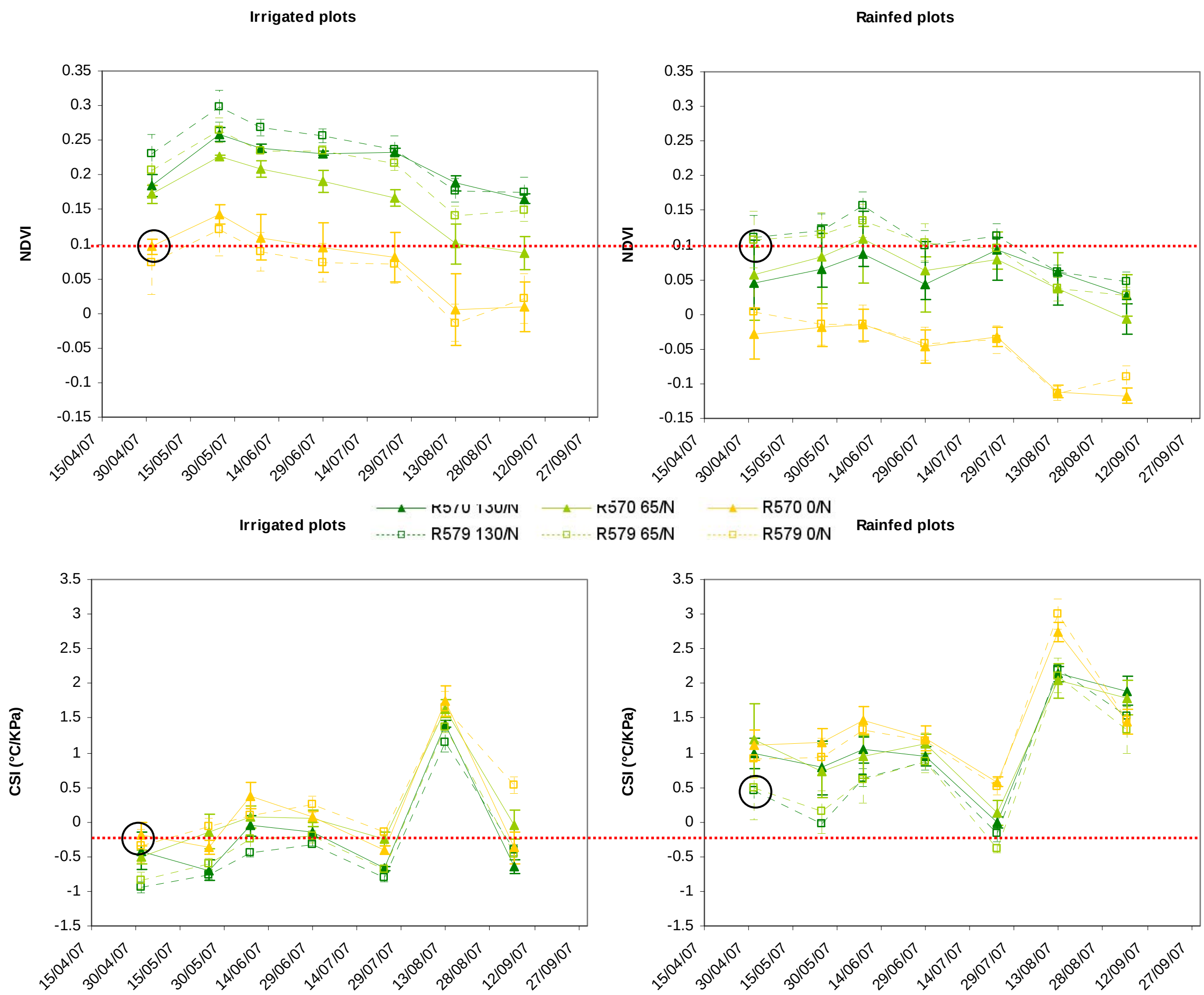

Fig.4 – Evolution of NDVI and CSI for each combination of “cultivar / nitrogen input” under irrigated (left) and rainfed (right) mode. Error bars indicate ± 1/2 standard deviation of the mean (*n* = 3).

Another way to describe and explain NDVI and CSI variations is by making multiple linear regression analysis between the indices and the biophysical crop parameters. Concerning NDVI, results (Table.1) show that NDVI is more responsive to the LAI until the end of the growth period (end of July), and then to SPAD during senescence stage. The sensitivity of NDVI to humidity is lower. At the beginning of the experiment, the NDVI is thus sensitive to increase of foliage. Then, during maturation, the leaf color becomes the main illustrative factor.

For CSI, as for NDVI at the beginning of the experiment, the LAI is the main illustrative variable. Then, when vegetation is, for the majority of treatments, fully developed (LAI above 4.5), the CSI becomes more sensible to humidity. No sensitivity to SPAD is noticed.

NDVI	25/05/07	08/06/07	29/06/07	23/07/07	13/08/07	05/09/07	all dates
LAI	**87.7%**	8.2%	**74.4%**	**71.1%**		16.6%	12.2%
Humidity	7.9%	18.0%	25.6%	21.6%	11.2%	7.2%	12.0%
SPAD	4.4%	**73.8%**		7.3%	**88.8%**	**76.2%**	**75.8%**
R²	0.89	0.85	0.80	0.82	0.74	0.81	0.78

Table.1 – Results of the multiple linear regression analysis for NDVI.

CSI	25/05/07	08/06/07	29/06/07	23/07/07	13/08/07	05/09/07	all dates
LAI	**85.2%**	**80.7%**	11.8%	24.4%	**76.1%**		16.2%
Humidity	14.8%	19.3%	**88.2%**	**75.6%**	23.9%	**100.0%**	**83.8%**
SPAD							
R²	0.80	0.72	0.68	0.75	0.50	0.26	0.31

Table.2 – Results of the multiple linear regression analysis for CSI.

Figure 6 summarise the relationships between NDVI or CSI and the two main illustrative variables for each index.

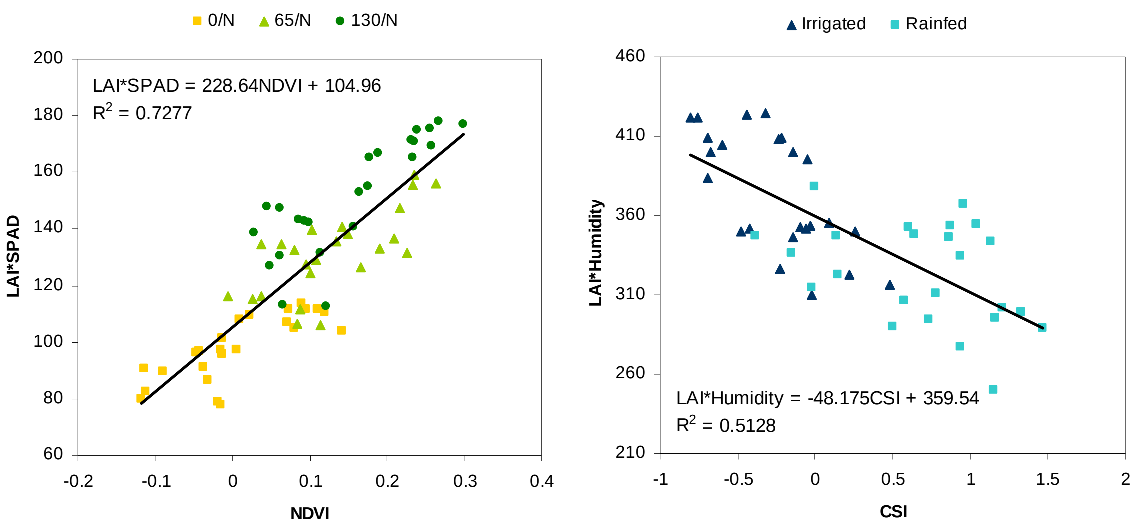

Fig.5 – Relationships between NDVI and LAI*SPAD (left) and between CSI and LAI*Humidity (right).

The following figure shows examples of the spatial distribution of NDVI and CSI of the experimental field for 3 dates. At the beginning of the experiment (2 May – Fig.), when both NDVI and CSI are influenced by LAI, the spatial patterns of the two indices corresponds for water treatments with highest NDVI corresponding to lowest CSI. However, less variability is observed on CSI images between the different nitrogen treatments or cultivar. On 8 August, as both irrigated and rainfed treatment are under water stress, CSI is high for all combinations of treatments.

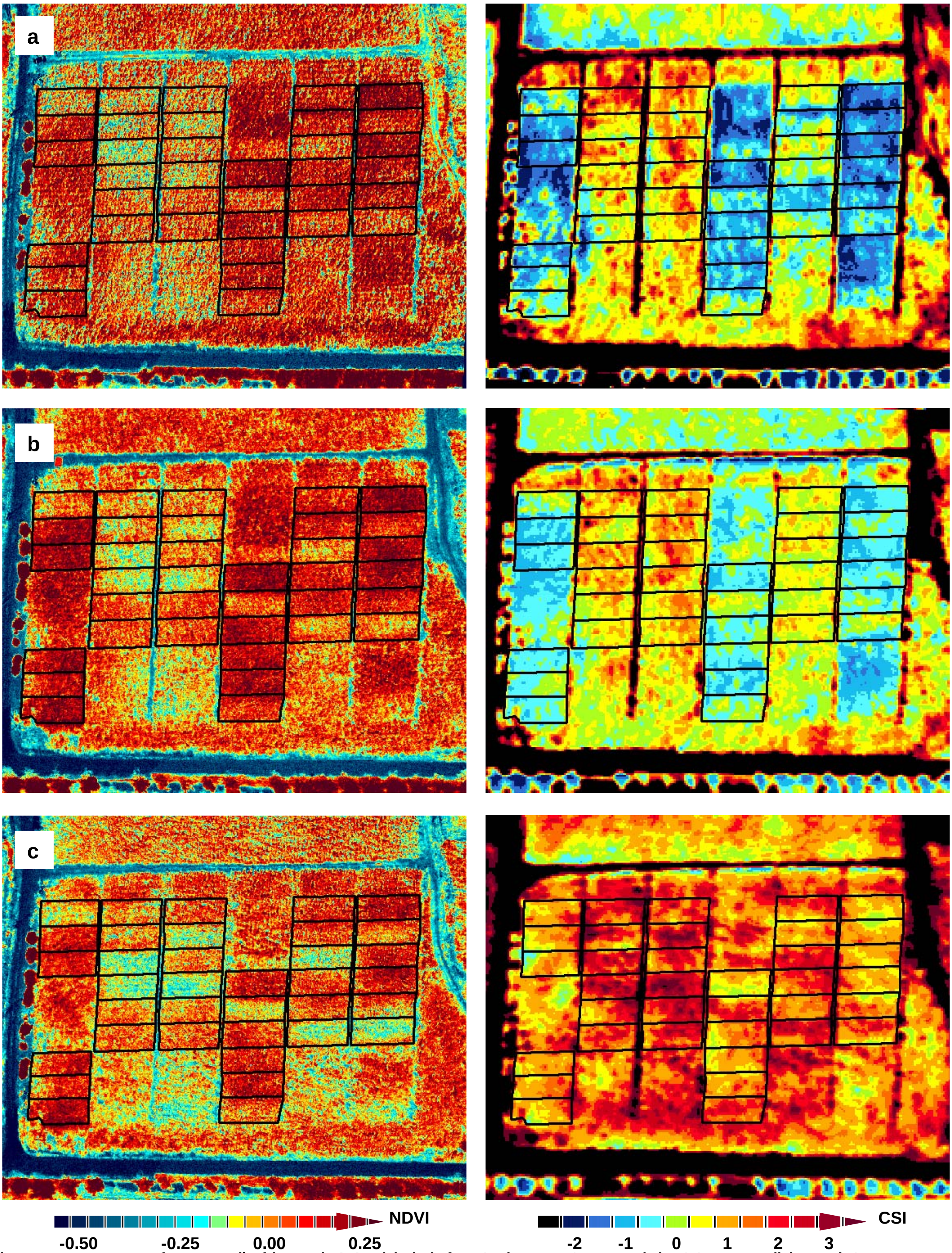

Fig.5 – Images of NDVI (left) and CSI (right) for 3 dates: 2 May (a), 29 June (b) and 8 August (c).

Combination of the two indices

As seen previously, NDVI and CSI present a different sensitivity to crop biophysical parameters. Both indices are logically influenced by LAI, but NDVI is more sensitive to leaf color (SPAD), while for CSI, the humidity prevails. The combined use of these two indices can thus provide new information for a better understanding of crop status. For example, in figure 4, one can see that for a given date, a same value of NDVI (red dotted line) can be induced by different combination of cropping practices (black circle): “R570 – Irrigated – 0/N” or “R579 – Rainfed – 130/N”. However, for the same date, the CSI is different for those two combinations of treatments and is higher for rainfed crop, allowing the identification of a stress du to a lack of water.

Conclusion

New technologies and advancement in remote sensing sensors provide nowadays a wide range of ways to help on crop management. Understanding crop response to different agricultural practices is a key point for a better interpretation of remotely sensed-derived stress indices.

The preliminary results of our study show the necessary combination of optical and thermal indices for identification of stress causes.

In following steps, we will focus on consequences of cropping practices on the concept of Vegetation Index/Temperature (VIT) (Moran et al., 1994) that allows the application of the Crop Water Stress Index (CWSI) (Jackson et al., 1981) for partially covered canopies.

Acknowledgments

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